Computers and Electronics in Agriculture 74 (2010) 168–173

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Application note

A low-cost microcontroller-based system to monitor crop temperature and water status

Daniel K. Fisher[a,*], Hirut Kebede[b,1]

[a] USDA Agricultural Research Service, Application and Production Technology Research Unit, 141 Experiment Station Rd., Stoneville, MS 38776, USA
[b] USDA Agricultural Research Service, Crop Genetics Research Unit, 141 Experiment Station Rd., Stoneville, MS 38776, USA

ARTICLE INFO

Article history:
Received 29 September 2009
Received in revised form 11 June 2010
Accepted 27 July 2010

Keywords:
Microcontrollers
Sensors
Infrared thermometer
Air temperature
Soil temperature
Datalogging
Soil moisture

ABSTRACT

A prototype system was developed and constructed for automating the measurement and recording of canopy-, soil-, and air temperature, and soil moisture status in cropped fields. The system consists of a microcontroller-based circuit with solid-state components for handling clock/calendar, sensor power, and data storage and retrieval functions. Sensors, including an analog soil moisture sensor, analog and digital temperature sensors, and a digital infrared thermometer, are widely available and inexpensive. The circuit board and sensor assemblies require approximately 4 h to construct and test, and material costs totaled approximately US$84. Systems were built and tested during the 2009 growing season in a corn field to evaluate performance and suitability under local conditions. The sensors performed according to manufacturers' specifications, with accuracies of $\pm 0.4\,^{\circ}$C, $\pm 1.4\,^{\circ}$C, and $\pm 0.3\,^{\circ}$C for air-, soil-, and canopy-temperature measurements, respectively. Soil moisture sensors were calibrated and provided measurements within ± 2 kPa of the manufacturer's values. Reliability of data collection and storage averaged 91%, with most bad or missing data occurring during periods of inclement weather and electrostatic interference.

Published by Elsevier B.V.

1. Introduction

Automatic data-acquisition systems are currently used in a wide variety of applications which include cropland environmental monitoring. The benefits of automated measurements are numerous. Data are collected continuously throughout the cropping season, and measurements are made day and night, on weekends, and during inclement weather, when manual measurements would likely not be collected. Sensors installed in a fixed location ensure consistency in measurements (same location in the field, same part of the crop/plant, and same physical orientation of the sensors). Reducing trips to the field helps minimize possible plant damage, soil compaction, and other impacts of human traffic in the area under study.

There are many advantages in developing microcontroller-based circuits and incorporating new sensor technologies into agricultural applications. Microcontrollers and solid-state sensors can be found in many commercial, industrial, and consumer applications. Many sensors and auxiliary components (memory chips, clocks, etc.) are designed to interface directly with microcontrollers, simplifying circuit design and modification. A variety of programming languages are available, allowing the programmer to access sophisticated and complex features and create applications without having to learn each microcontroller's native assembly language. Components are very inexpensive, and can be obtained in most parts of the world via a number of suppliers.

Moisture deficit stress and high temperature are two of the major environmental factors that affect crop production. The amount of water used by a crop at any time depends, among other things, on moisture availability in the soil, air temperature, and soil temperature. The determination of soil moisture status is of major consideration regarding plant–water relations. Soil temperature measurement is important in studying how extreme temperatures can limit the availability of water to the roots and cause water deficit stress (Gavito et al., 2001; Lambers, 2008).

Canopy temperature (CT) relative to ambient air temperature is often used to assess plant stress caused by moisture deficit or high temperature (González-Dugo et al., 2006; Reynolds et al., 2007). The correlation between CT and moisture deficit stress is based on the principle that as a crop transpires, the evaporated water cools the leaves to a temperature below that of the air (Jackson, 1982). In crop improvement research for drought and heat-stress tolerance, this approach is used in identifying genotypes that maintain lower CT as compared to other genotypes under the same moisture deficit

* Corresponding author. Tel.: +1 662 686 5342; fax: +1 662 686 5372.
E-mail addresses: daniel.fisher@ars.usda.gov (D.K. Fisher), hirut.kebede@ars.usda.gov (H. Kebede).
[1] Tel.: +1 662 686 3125; fax: +1 662 686 5218.

0168-1699/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.compag.2010.07.006

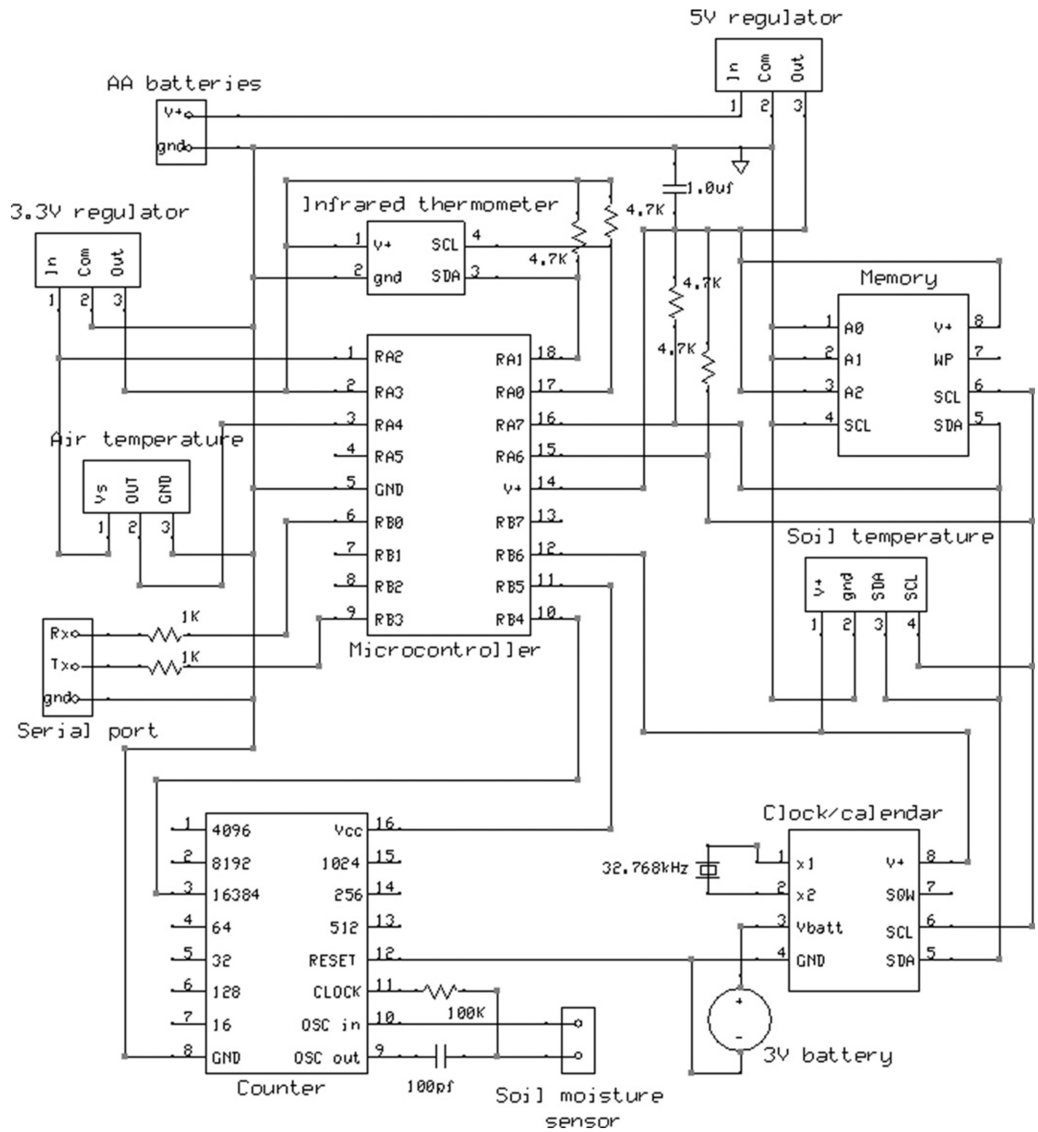

Fig. 1. Electrical schematic of circuit board.

or heat-stress conditions (Balota et al., 2008; Kashiwagi et al., 2008; Rashid et al., 1999).

In production fields, CT measurements have been used mainly in scheduling irrigations. Canopy temperature is subject to rapid fluctuations over the course of a day, and factors such as air temperature, wind speed, relative humidity, solar irradiance, and soil moisture, which all affect plant evapotranspiration, play a role (Jensen et al., 1990). A variety of methods have been tested (Jackson et al., 1981; Kjelgaard and Stockle, 1996; Wanjura and Upchurch, 2006) but high humidity can be a complicating factor (Bockhold et al., 2003).

A system was needed for monitoring crop and canopy conditions in a large number of locations to study drought and temperature stress effects on crops. The objective of the project was to

Table 1
List of circuit components and sensors.

Description	Part number	Manufacturer	Cost (US$)
Microcontroller	PIC16F88	Microchip Technologies	2.60
Real-time clock	DS1307	Dallas Semiconductor	3.00
Memory	24LC1025	Microchip Technologies	4.00
Counter	74HC4060	Fairchild Semiconductor	0.50
Voltage regulator	LP2950	National Semiconductor	0.50
Voltage regulator	UA78M33C	Texas Instruments	1.00
Miscellaneous (oscillator, resistors, capacitors, headers, sockets, batteries, enclosure, cables, etc.)			13.00
Air temperature sensor	LM35	National Semiconductor	1.00
Soil temperature sensor	TC74	Microchip Technologies	1.50
Infrared temperature sensor	MLX90614	Melexis	27.00
Soil moisture sensor	200-SS	Irrometer	30.00

Note: Parts are available from online sources such as Digikey (www.digikey.com), Allied Electronics (www.alliedelec.com), and Newark Electronics (www.newark.com).

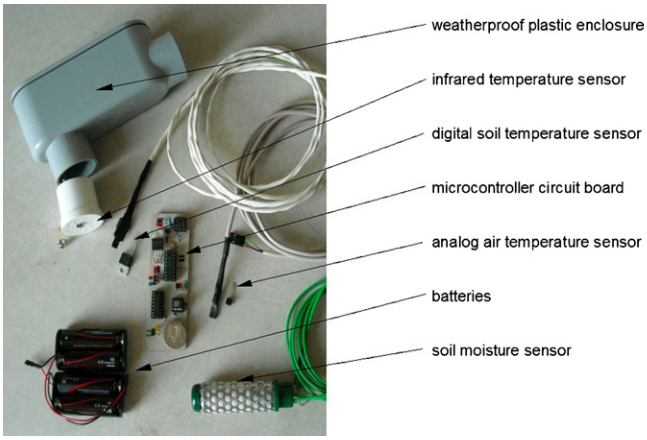

Fig. 2. Circuit board and sensor components.

design an inexpensive microcontroller-based system suitable for measuring canopy-, soil-, and air temperature, and soil moisture status. Design criteria included automated measurements and data collection, low cost (<$100), ease of manufacture, and reliable performance.

2. General description of the microcontroller system

A circuit was designed to automate the measurement and recording of soil moisture and plant-, soil-, and air temperature sensors. The circuit is based on a programmable microcontroller, with sensors and peripheral components connected to and controlled by the microcontroller. Circuit components were selected which provided the desired functions, integrated easily with the microcontroller, were inexpensive and readily available, and operated with low voltage and current consumption, allowing for battery-powered operation.

2.1. Circuit design

The main components of the circuit are a microcontroller, real-time clock, nonvolatile memory, voltage regulators, binary counter, and RS232 interface. The circuit is based on another design used for monitoring soil moisture sensors (Fisher, 2007), but modified to use a more powerful microcontroller and to interface with additional sensors. A schematic diagram of the circuit is shown in Fig. 1, and a list of main circuit components is shown in Table 1. A photograph of the completed circuit board and sensors is shown in Fig. 2.

The microcontroller is a PIC16F88 (Microchip Technologies, Chandler, AZ), an 18-pin, 8-bit microcontroller with analog- and digital-signal features, a low-power sleep mode, and external interrupt and serial-communications capabilities. Analog-voltage signals can be measured with built-in analog-to-digital converters, which allow up to 10-bit resolution, and a variety of digital-signal communications protocols are supported. The low-power sleep mode allows the microcontroller to conserve energy between active measurement intervals, enabling the circuit to operate for long periods on battery power. Interrupt and serial-communications capabilities allow the microcontroller to wake up and interact with an external device, such as a handheld computer to accept user inputs or transfer data.

A battery pack, consisting of four AA-size, 1.5 V alkaline batteries, provides an unregulated voltage to power the circuit. Most of the components in the circuit are designed to operate from a 5 V supply, and an LP2950 5 V voltage regulator (National Semiconductor, Santa Clara, CA) is used to convert the battery voltage to a stable 5 V supply. An additional 3.3 V regulator, a UA78M33C (Texas Instruments, Dallas, TX), is used for power and to provide the reference voltage for the microcontroller's analog-to-digital converters.

The Philips Inter-IC communications protocol, also referred to as I^2C or I2C (Philips Semiconductors, The Netherlands), is commonly used for interfacing peripheral devices with a microcontroller, and is very convenient for connecting components to a circuit. I2C communications are enabled via a bidirectional, two-wire bus, and all I2C components in a circuit are connected via these two lines. This allows for interfacing a large number of I2C-compatible devices using only two pins on the microcontroller. Each I2C component has a unique identifying number, and the microcontroller communicates with each individual component via this identifier. Circuit components which operate under the I2C protocol include the DS1307 real-time clock/calendar (Dallas Semiconductor, Dallas, TX) and the 24LC1025 memory module (Microchip Technologies, Chandler, AZ). The real-time clock provides date and time information, and is used to determine the timing of sensor measurements and provide a time and date stamp for recorded data. The memory module stores data in bytes (8-bit values ranging from 0 to 255), and has the capacity to record 2^{17}, or 131,072, data bytes.

A 74HC4060 binary counter (Fairchild Semiconductor, San Jose, CA) is used to provide an alternating excitation to the soil moisture sensor and to measure the sensor's output. A resistor–capacitor (R–C) network connected to the input pins of the counter acts as an oscillator, which outputs an alternating signal whose frequency is a function of the R–C network values. The moisture sensor acts as a variable resistor, and is connected as part of the R–C network. The output signal is input to the microcontroller, which measures the frequency and converts it to moisture status through a calibration equation.

The user interfaces with the circuit using a terminal program running on a notebook or handheld computer. The computer communicates with the microcontroller circuit via the RS232 serial interface. The serial interface is connected to the microcontroller's interrupt pin, and the microcontroller is programmed to wake up and enter a user-interface routine whenever a signal is detected on this pin. A menu allows the user to download data stored in the memory chip, reset the date and time in the real-time clock, enter an identifying number for the circuit board, or enter a test-mode routine. To download stored data, the user enters the number of days of data to download, and data are output in plain ASCII text. If the user accesses the test-mode routine, sensor measurements are made and output through the RS232 connection in real time, allowing the user to ensure that the real-time clock and circuit-board identifying numbers are set and that all sensors are connected and functioning properly.

The microcontroller is a programmable device, with the functionality of the device determined by the programmer's code entered into it. Programming was accomplished using the PicBasicPro compiler (microEngineering Labs, Colorado Springs, CO). The PicBasicPro compiler allows the programmer to write a microcontroller program in an English-like BASIC language, which is then converted into the microcontroller's native assembly language. The compiler greatly simplifies the programming process, and allows many sophisticated microcontroller functions to be enabled with simple, one-line commands. The compiled program is loaded into the microcontroller via microEngineering Labs' EPIC Plus PICmicro Programmer, a hardware device connected to a desktop computer running under a Windows environment, and operated using microEngineering Labs' proprietary EPICWin software. The program, in BASIC text format or in the compiled, assembly language form, is freely available by contacting the authors.

2.2. Sensors

An infrared thermometer (IRT) module, model MLX90614 (Melexis, Concord, NH), is used to obtain plant canopy (leaf) temperature measurements. The MLX90614 consists of an infrared-sensitive thermopile detector chip and a signal conditioning chip integrated into a single unit. The sensor's on-board 17-bit analog-to-digital (A–D) converter and signal-processing electronics are contained in a small metal package approximately 8 mm in diameter and 4 mm high. An optical filter is integrated into the package to provide ambient and sunlight immunity, resulting in sensitivity to infrared radiation in the 5.5- to 14-μm range. The microcontroller communicates with the sensor using the Philips I2C communications protocol, and temperature measurements are output in a digital format with an accuracy of ±0.5 °C and a resolution of 0.02 °C.

Soil temperature measurements are collected with a TC74 digital temperature sensor (Microchip Technologies, Chandler, AZ). The TC74 sensor contains an on-board thermal sensing element and signal-processing electronics to provide a temperature measurement as an 8-bit (single byte) digital word with an accuracy of ±2 °C and a resolution of 1 °C. The temperature sensor operates from a 5 V supply and uses the I2C communications protocol to output the digital temperature measurement.

Air temperature measurements are made using an LM35 analog temperature sensor (National Semiconductor, Santa Clara, CA). The LM35 sensor is powered from a 5 V supply, and outputs an analog-voltage signal in proportion to its temperature. The output signal is measured with one of the microcontroller's built-in A–D converters, and a calibration equation supplied by the manufacturer is used to convert the voltage signal to temperature, with an accuracy of ±0.5 °C.

A measure of the soil's moisture status is made with a Watermark 200-SS (Irrometer, Riverside, CA) water-potential sensor. The Watermark sensor is composed of a granular-matrix whose water content changes in response to the water potential of the surrounding soil. As the water content of the sensor changes, so does its electrical resistance. The resistance is converted to an alternating signal via the 74HC4060 binary counter, with frequency proportional to resistance, and a calibration equation converts the frequency to soil–water potential.

A calibration routine was developed to convert moisture-sensor resistance to water potential. The routine consisted of measuring the frequency of the alternating output signal over the range of resistance values expected from the sensor when installed in the field. A series of standard, fixed-value carbon resistors were placed in the circuit in place of the Watermark sensor, and the frequency at each resistance value was recorded. A model 30 KTCD-NL Watermark Meter (Irrometer Co., Riverside, CA, USA), a handheld meter commonly used to manually monitor Watermark sensors, was used to obtain a relationship between resistance and water-potential values. The two relationships, resistance as a function of frequency, and water potential as a function of resistance, were then combined. A curve was fit to the data, resulting in a calibration equation for calculating water potential as a function of frequency. Two different resistance to water potential calibration equations were determined, one for potentials in the range of 0 to 10 kPa, and a second for the range of 11–200 kPa, to agree with the calibration equations built into the Watermark Meter (Eldredge and Shock, 1993; Shock and Barnum, 1998). Results from the calibration routine for the 10 circuit boards are shown in Fig. 3. Fitting a single calibration equation using all the data resulted in a standard error of 5 kPa. To improve the accuracy of the water-potential measurements, a calibration equation was developed for each circuit board, reducing the standard error to about 2 kPa. An example calibration is shown in Fig. 3.

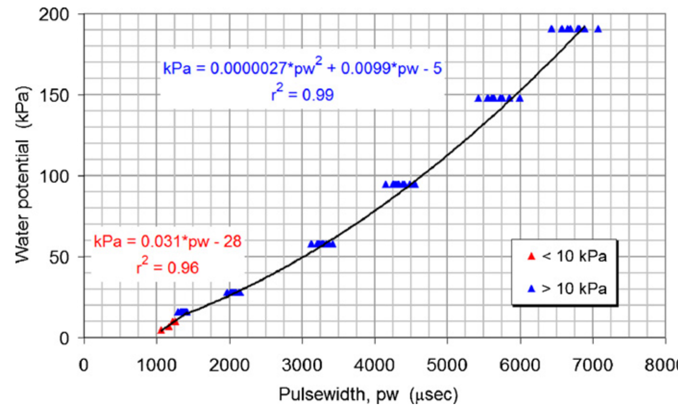

Fig. 3. Soil moisture sensor calibration equation for converting pulsewidth (pw) to water potential (kPa).

2.3. Circuit operation

The microcontroller was programmed to handle all power, measurement, data-recording, and user-interface functions of the circuit. Since the circuit was designed to operate from battery power, low current consumption was of importance, and the circuit is programmed to spend most of its time in a low power, sleep mode. Measurements were programmed to be taken at 1-h interval, at the beginning of each hour. At approximately 1-min interval, the microcontroller wakes and reads the time from the real-time clock. If it is not time to take measurements, the microcontroller puts the circuit back to sleep for another minute. Current consumption is approximately 13 mA during active measurement periods, and drops to 0.34 mA while in sleep mode. Using standard AA alkaline batteries with a capacity of 2500 mAh, this results in an expected battery life of 280 days.

At the beginning of a measurement interval, the microcontroller supplies power to the circuit and sensors. Each sensor is read 10 times and the readings are averaged. A soil moisture reading is taken by measuring the frequency of the alternating signal from the binary counter. The average frequency is input to a calibration equation and converted to water potential, in kilopascals (kPa). A soil temperature measurement is taken by reading the TC74 digital temperature sensor using the I2C communications protocol. An air temperature reading is taken by measuring the signal voltage output from the LM35 sensor with one of the microcontroller's A–D converters and converting to temperature. Canopy temperature is measured with the MLX90614infrared thermometer using the I2C communications protocol. The sensor first makes a measurement of its own internal temperature, which is used to correct the infrared temperature reading for ambient temperature conditions.

Data are then stored in the memory chip. Date (month, day, and year), time (hour), soil moisture status (kPa), soil temperature (°C), air temperature (°C), and canopy temperature (°C) are written to the memory chip at each measurement interval. Since the memory chip can only store byte values (whole numbers between 0 and 255), temperature readings, which contain decimal values must be stored in two locations. The whole part is stored as a byte in one memory location and the decimal part is stored as a byte in the next location. The original data values are reconstructed by joining the whole and decimal parts when the user downloads the data to a computer. With a measurement interval of 1 h and 11 data bytes stored each hour, the memory chip has the capacity to store an entire year's data without any data being overwritten. Following data storage, the microcontroller program turns power off to the sensors, puts the circuit in a low-power mode, and goes to sleep.

Circuit boards were designed and constructed by hand by personnel at the USDA ARS facility in Stoneville, MS. Microcontrollers were programmed, and each board was calibrated and tested. Sensors were attached to cables, and then enclosed in a layer of heat-shrink tubing to protect them from moisture when installed in the field. Connectors were attached to the other end of the cables to allow connection to the circuit boards. Labor required to fabricate, test and assemble each circuit board and sensor system consisted of approximately 2 h for circuit-board fabrication, 1 h for sensor cable assembly, and 1 h for final assembly and testing. Costs of the circuit and sensor components are shown in Table 1, with a cost of materials of US$24.60 for the circuit board and US$59.50 for the sensors, for a total material cost of US$84.10 for each complete system.

3. Field deployment and testing of the system

Prior to deployment in the field, the temperature sensors were tested to examine the accuracy and variability of sensor measurements. Seven samples of each of the three temperature sensors were placed in a controlled-temperature environment, and tested over a range of temperatures. Temperatures measured with the LM35 sensors were accurate to within ±0.4 °C, with a maximum standard deviation for any sensor of ±0.11 °C. Measurements made with the TC74 sensors were within ±1.4 °C, with a maximum standard deviation of ±0.25 °C. Measurements made with the MLX90614 infrared temperature sensors were within ±0.3 °C, with a maximum standard deviation of ±0.04 °C. While these measurements were within the specifications provided by the manufacturers, the sensors could be individually calibrated to remove the slight sensor-to-sensor variability.

The prototype system was deployed in a research field at the USDA ARS's Jamie Whitten Delta States Research Center, Stoneville, MS, USA, in the summer of 2009 to test system performance and reliability. Soil moisture and soil temperature sensors were installed at a depth of 30 cm below the soil surface in 10 plots planted to corn under irrigated and non-irrigated conditions. Infrared canopy-temperature sensors were mounted inside thick-walled PVC plastic enclosures and attached to tall fiberglass poles, located near the center of each plot, with a metal hose clamp. The height of the sensors could be adjusted by loosening the clamps and repositioning the sensors on the poles, allowing the sensors to be moved periodically as the crop grew. The corn rows ran east and west, and the sensors were oriented facing north, aimed at the south-facing sunlit leaves of the crop. The circuit board and battery pack were placed inside a plastic enclosure mounted on a short, wooden stake, with sensor cables routed to the circuit board through a hole in the bottom of the box.

Throughout the growing season, data were downloaded during periodic visits to each location. A Palm III handheld computer was connected to the circuit board via a serial cable, and data were downloaded using a terminal program on the computer. These data, in standard ASCII text format, were later transferred to a desktop computer for examination, analysis, and storage. At the end of the season, the reliability of the data collection systems were evaluated by examining the amount of data collected and the amount of bad or missing values. The percentage of good data averaged 93%, and ranged from 86 to 99% for the individual circuit boards. Instances of bad or missing data usually occurred during periods of inclement weather, when high humidity and/or lightening affected the electronic circuitry in the unsealed plastic enclosures housing the circuit boards.

Data were collected with the prototype systems throughout the growing season to compare environmental conditions under irrigated and non-irrigated conditions. An example of data collected in one corn plot under irrigated conditions is shown in Fig. 4 for a 7-day period in July 2009. The graph shows measurements of soil moisture and soil-, air-, and canopy temperatures collected at hourly intervals. The data showed that canopy temperatures in the non-irrigated plots were 2–4 °C higher between 12:00 and 16:00 each day than in the irrigated plots, with highest temperatures ranging from 29–34 °C to 28–30 °C for the non-irrigated and irrigated plots, respectively. Similarly, soil temperature at the 30 cm depth was about 3 °C higher in the non-irrigated plots at all times. During this period of time, soil water potential ranged from −17 to −45 kPa in the irrigated plots and from −180 to −200 kPa in the non-irrigated plots, indicating that there was significantly less soil moisture available for the corn plants in the non-irrigated plots. Low moisture levels in the soil and air temperature as high as 36 °C in the non-irrigated plots would make it harder for the corn plants in the non-irrigated plots to meet the atmospheric evaporative demand and cool off the leaves which consequently resulted in higher CT values in these plots. This information collected using the microcontroller based system will help monitor water deficit stress on the plants and, together with other physiological parameters, can assist in evaluating genotypes for drought stress tolerance.

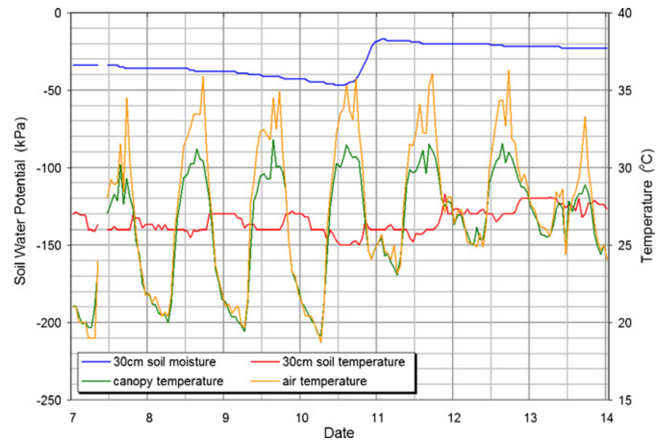

Fig. 4. Hourly soil moisture, soil temperature, canopy temperature, and air temperature measurements over a 7-day period in July 2009 from an irrigated corn plot.

4. Summary

A measurement system was designed for monitoring soil moisture, and soil-, air-, and canopy-temperature levels in cropped fields. The microcontroller-based system consists of inexpensive electronic components and solid-state sensors, and is designed for continuous, automated monitoring of crop conditions. The programmable microcontroller offers a wide variety of features, allows for simple connection and operation of peripheral components and sensors, and can be programmed to suit the needs of the user. Circuit boards and sensor assemblies were constructed and deployed to evaluate their performance and suitability under local conditions. Costs of the circuit components and sensors were US$24.60 for the circuit board and US$59.50 for the sensors, for a total material cost of US$84.10 for each complete system.

The systems were deployed and collected data during the 2009 growing season, and provided valuable information on crop and canopy conditions. The systems will be deployed next season to compare conditions among corn genotypes for use in evaluating stress tolerance. Additional sensors for relative humidity, wind speed and solar radiation may also be installed and tested, as these are additional factors that influence canopy temperature. Measurements will also be used to evaluate the use of infrared thermometers for irrigation scheduling under conditions of high humidity in the region.

4.1. Disclaimer

Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the U.S. Department of Agriculture, and does not imply approval of the product to the exclusion of others that may be available.

Acknowledgements

The authors wish to thank Mr. Kevin Colvin, Electronics Technician, for his electronics expertise and assistance in designing and constructing the circuit boards, and for his assistance in field testing of the instrumentation, and Mr. Roderick Patterson, Agricultural Science Research Technician, for his expertise and assistance in field operations during this study.

References

Balota, M., Payne, W.A., Evett, S.R., Peters, T.R., 2008. Morphological and physiological traits associated with canopy temperature depression in three closely related wheat lines. Crop Science 48, 1897–1910.

Bockhold, D.L., Thompson, A.L., Sudduth, K.A., Henggeler, J.C., 2003. Irrigation scheduling using infrared thermometers to measure canopy temperature on cotton and soybean. Paper No. 032143. In: Proceedings of the ASAE Annual International Meeting, Las Vegas, NV, USA.

Eldredge, E.P., Shock, C.C., Stieber, T.D., 1993. Calibration of granular matrix sensors for irrigation management. Agronomy Journal 85, 1228–1232.

Fisher, D.K., 2007. Automated collection of soil-moisture data with a low-cost microcontroller circuit. Applied Engineering in Agriculture 23 (4), 493–500.

Gavito, M.E., Curtis, P.S., Mikkelsen, T.N., Jakobsen, I., 2001. Interactive effects of soil temperature, atmospheric carbon dioxide and soil N on root development, biomass and nutrient uptake of winter wheat during vegetative growth. Journal of Experimental Botany 52, 1913–1923.

González-Dugo, M.P., Moran, M.S., Mateos, L., Bryant, R., 2006. Canopy temperature variability as an indicator of crop water stress severity. Irrigation Science 24, 233–240.

Jackson, R.D., 1982. Canopy temperature and crop water stress. Advances in Irrigation 1, 43–85.

Jackson, R.D., Idso, S.B., Reginato, R.J., Pinter Jr., P.J., 1981. Canopy temperature as a crop water stress indicator. Water Resources Research 17, 1133–1138.

Jensen, H.E., Svendsen, H., Jensen, S.E., Mogensen, V.O., 1990. Canopy-air temperature of crops grown under different irrigation regimes in a temperate humid climate. Irrigation Science 11, 181–188.

Kashiwagi, J., Krishnamurthy, L., Upadhyaya, H.D., Gaur, P.M., 2008. Rapid screening technique for canopy temperature status and its relevance to drought tolerance improvement in chickpea. Journal of Semi-Arid Tropical Agricultural Research, 6.

Kjelgaard, J.F., Stockle, C.O., Evans, R.G., 1996. Accuracy of canopy temperature energy balance for determining daily evapotranspiration. Irrigation Science 16, 149–157.

Lambers, H., Chain III, F.S., Pons, T.L., 2008. Plant Physiological Ecology. Springer Science, New York, NY, p. 347.

Rashid, A., Stark, J.C., Tanveer, A., Mustafa, T., 1999. Use of canopy temperature measurements as a screening tool for drought tolerance in spring wheat. Journal of Agronomy and Crop Science 182, 213–237.

Reynolds, M.P., Pierre, C.S., Saad, A.S.I., Vargas, M., Condon, A.G., 2007. Evaluating potential genetic gains in wheat associated with stress-adaptive trait expression in elite genetic resources under drought and heat stress. Crop Science 47, 172–189.

Shock, C.C., Barnum, J., Seddigh, M., 1998. Calibration of Watermark soil moisture sensors for irrigation management. In: Proceedings of the International Irrigation Association Annual Meeting, Irrigation Association, San Diego, CA, pp. 139–146.

Wanjura, D.F., Upchurch, D.R., Mahan, J.R., 2006. Behavior of temperature-based water stress indicators in BIOTIC-controlled irrigation. Irrigation Science 24, 223–232.